Baryonic and Non-Baryonic Dark Matter

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Abstract

Cosmological nucleosynthesis calculations imply that there should be both non-baryonic and baryonic dark matter. Recent data suggest that some of the non-baryonic dark matter must be "hot" (i.e. massive neutrinos) and there may also be evidence for "cold" dark matter (i.e. WIMPs). If the baryonic dark matter resides in galactic halos, it is likely to be in the form of compact objects (i.e. MACHOs) and these would probably be the remnants of a first generation of pregalactic or protogalactic Population III stars. Many candidates have been proposed - brown dwarfs, red dwarfs, white dwarfs or black holes - and at various times each of these has been in vogue. We review the many types of observations which can be used to constrain or exclude both baryonic and non-baryonic dark matter candidates.

1. Introduction

Evidence for dark matter has been claimed in many different contexts. There may be *local* dark matter in the Galactic disc, dark matter in the *halos* of our own and other galaxies, dark matter associated with *clusters* of galaxies and finally - if one believes that the total cosmological density has the critical value - smoothly distributed *background* dark matter. Since dark matter probably takes as many different forms as visible matter, it would be simplistic to assume that all these dark matter problems have a single solution. The local dark matter is almost certainly unrelated to the other ones and, while the halo and cluster dark matter would be naturally connected in many evolutionary scenarios, there is a growing tendency to regard the unclustered background dark matter as different from the clustered component. This is because the latest supernovae measurements indicate that the cosmological expansion is accelerating, which means that the total density must be dominated by some form of "exotic" energy with negative

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pressure (possibly a cosmological constant).

The combination of the supernovae and microwave background observations suggest that the density parameters associated with the exotic (unclustered) component and the ordinary (positive pressure) *matter* component are $\Omega_X = 0.8 \pm 0.2$ and $\Omega_M = 0.4 \pm 0.1$ respectively (Turner 1999). This is compatible with the total density parameter being 1, as expected in the inflationary scenario, but does not definitely require it. This paper will focus exclusively on the matter component of the cosmological density, with particular emphasis on the question of how much of this is baryonic and non-baryonic. We will also be interested in the relative contributions of hot and cold non-baryonic matter. As emphasized by Turner (1999), each of these components seem to be required and it is remarkable that all their densities are within one or two orders of magnitude of each other. Why this should be remains a mystery but we will not explore this further here.

2. Evidence for Baryonic and Non-Baryonic Dark Matter

The main argument for both baryonic and non-baryonic dark matter comes from Big Bang nucleosynthesis calculations. This is because the success of the standard picture in explaining the primordial light element abundances only applies if the baryon density parameter lies in the range (Copi et al. 1995)

$$0.007h^{-2} < \Omega_B < 0.022h^{-2} \tag{1}$$

where h is the Hubble parameter in units of 100 km s^{-1} Mpc^{-1}. A few years ago the anomalously high deuterium abundance measured in some intergalactic Lyman-α clouds suggested that the nucleosynthesis value for Ω_B could be lower than indicated by eqn (1) (Carswell et al. 1994, Songaila et al. 1994, Rugers & Hogan 1996, Webb at al. 1997). However, the evidence for this has always been strongly disputed (Tytler et al. 1996) and recent studies of the quasars Q1937 and Q1009 suggest that the deuterium abundance is 3.3×10^{-5} (Burles & Tytler 1998). This corresponds to the range

$$0.018h^{-2} < \Omega_B < 0.020h^{-2}, \tag{2}$$

which is much tighter than indicated by eqn (1) (Burles et al. 1999).

Both eqns (1) and (2) suggest that the upper limit on Ω_B is well below 1, which implies that no baryonic candidate could provide the matter density required by large-scale structure observations. This conclusion also applies if one invokes inhomogeneous nucleosynthesis since one requires $\Omega_B < 0.09h^{-2}$ even in this case (Mathews et al. 1993). On the other hand, the upper limit on Ω_B allowed

by eqns (1) and (2) almost certainly exceeds the density of visible baryons Ω_V. A careful inventory by Persic & Salucci (1992) shows that the density in galaxies and cluster gas is

$$\Omega_V \approx (2.2 + 0.6h^{-1.5}) \times 10^{-3} \approx 0.003 \tag{3}$$

where the last approximation applies for reasonable values of h. A recent review by Hogan (1999) has updated this estimate of Ω_V: he replaces the factors in brackets in eqn (3) by 2.6 for spheroid stars, 0.86 for disc stars, 0.33 for neutral atomic gas, 0.30 for molecular gas and 2.6 for the ionized gas in clusters (assuming $H_o = 70$ km s^{-1} Mpc^{-1}). Although this is still well below the nucelosynthesis bound, this may not account for all components. Some of the baryons may be in an intergalactic medium; for example, Cen & Ostriker (1999) find that - in the context of the "Cold Dark Matter" scenario - half the mass of baryons should be in warm ($10^5 - 10^7$K) intergalactic gas at the present epoch. Another possibility is that the missing baryons could be in gas in groups of clusters. This has been emphasized by Fukugita et al. (1998), who argue that plasma in groups (which would be too cool to have appreciable X-ray emission) could provide all of the cosmological nucleosynthesis shortfall. Indeed the review by Hogan (1999) suggests that the ionized gas in groups could have a density parameter as high as 0.014. However, it must be stressed that this estimate is based on an extrapolation of observations of rich clusters and there is no direct evidence for this.

Which of the dark matter problems identified in Section 1 would be baryonic or non-baryonic? We have already seen that the dark matter in clusters would need to be mainly non-baryonic. On the other hand, the dark matter in galactic discs could certainly be baryonic: even if all discs have the 60% dark component envisaged for the Galaxy by Bahcall et al. (1992), this only corresponds to $\Omega_d \approx 0.001$, well below the nucleosynthesis bound. Indeed the disc dark matter would *need* to be baryonic in order to dissipate enough to form a disc. However, the Bahcall et al. claim is strongly disputed by Kuijken & Gilmore (1989) and Flynn & Fuchs (1995), In fact, recent Hipparcos observations suggest that the dark disc fraction is below 10% (Crézé et al. 1998).

The more interesting question is whether the halo dark matter could be baryonic. If the Milky Way is typical, the density associated with halos would be

$$\Omega_h \approx 0.03h^{-1}(R_h/100\text{kpc}), \tag{4}$$

where R_h is the (uncertain) halo radius, so the upper limit in eqn (1) implies that *all* the dark matter in halos could be baryonic providing $R_h < 70h^{-1}$kpc. This is marginally possible for our galaxy (Fich & Tremaine 1991), in which case the dark baryons could be contained in the remnants of a first generation of "Population

III" stars (Carr 1994). This corresponds to the "Massive Compact Halo Object" or "MACHO" scenario and has attracted considerable interest as a result of the LMC microlensing observations. Even if halos are larger than $70h^{-1}$kpc, and studies of the kinematics of other spirals by Zaritsky et al. (1993) suggest that they could be as large as $200h^{-1}$kpc, a considerable fraction of their mass could still be in stellar remnants.

On theoretial grounds one would expect the halo dark matter to be a *mixture* of WIMPs and MACHOs. For since the cluster dark matter must be predominantly cold, one would expect at least some of it to clump into galactic halos. The relative densities of the two components would depend sensitively on the formation epoch of the Population III stars. If they formed pregalactically, one would expect the halo ratio to reflect the cosmological background ratio (viz. $\Omega_B/\Omega_M \approx 0.1$). However, if they formed protogalactically, the ratio could be larger since the baryons could have dissipated and become more centrally concentrated than the WIMPs. In order to distinguish between the pregalactic and protogalactic scenarios, it is important to gain independence evidence about the formation epoch of the putative MACHOs. At moderate redshifts one can obtain a lower limit to the baryon density by studying Lyman-α clouds. The simulations of Weinberg et al. (1997) suggest that the density parameter of the clouds must be at least $0.017h^{-2}$ at a redshift of 2 and this is already close to the upper limit given by eqn (1). By today some of these baryons might have been transformed into a hot intergalactic medium or stars but this suggests that there was little room for any dark baryons before $z = 2$. On the other hand, we will see in Section 4 that background light constraints require that any massive Population III stars must have formed much earlier than this.

3. Non-Baryonic Candidates

Not only is the presence of non-baryonic dark matter required by cosmological nucleosynthesis arguments, but it also *expected* in the Big Bang scenario. This is because any particles which exist in nature must have existed profusely in the early Universe once the temperature exceeded their rest mass m_X. Some of these particles should therefore have survived as "relics" once the temperature fell below the value T_F at which their interactions froze-out. If the particles were relativistic at freeze-out ($T_F > m_X$), their current number density should be comparable to that of the microwave background photons, so one expects a relic density parameter $\Omega_X \approx (m_X/100eV)$. On the other hand, if they were non-relativistic at freeze-out ($T_F < m_X$), the current density declines with the particle mass ($\Omega_X \sim m_X^{-1.9}$) due to Boltzmann suppression. This gives two mass windows

in which Ω_X can be interesting: $M_X \approx 10 - 100$ eV and $M_X \approx 10 - 30$ GeV. Since the current velocity dispersion of the particles should be $< v^2 >^{1/2} \approx T/m_X$, which decreases with mass, particles in the smaller and larger ranges are termed "hot" and "cold" respectively. Particles can clump into bound objects of radius R and velocity dispersion σ only for

$$m_X > 30(R/10kpc)^{-1/2}(\sigma/100km/s)^{-1/4}eV \qquad (5)$$

and this gives a lower limit of 4 eV for clusters, 20 eV for galactic halos and 300 eV for dwarf galaxies.

Large-scale structure observations also require that the Universe be dominated by non-baryonic matter. This is because, in a purely baryonic universe, the density fluctuations required at decoupling to generate this structure would induce larger microwave background anisotropies than observed. However, this argument does not specify the nature of the non-baryonic dark matter precisely. The original "hot dark matter" (HDM) scenario, proposed in the early 1980s, assumed that it was in the form of neutrinos but that would be incompatible with the presence of dark matter in dwarf galaxies. This was superseded in the mid-1980s by the "cold dark matter" (CDM) scenario and this remained popular for almost a decade when it was found that it did not fit the latest large-scale structure data or give the observed gas fraction in clusters. In the mid-1990s models invoking a mixture of hot and cold dark matter (CHDM) became topical but these still had problems explaining the observed abundances of clusters, bright galaxies and Lyman-α clouds. Currently we have seen that a Universe containing both a cosmological constant and cold dark matter (ΛCDM) is in vogue and some people have considered a hot component ($\Lambda CHDM$) as well.

Eventually the combination of large-scale structure data and microwave background anisotropy measurements could determine the relative contributions of all the different types of dark matter very precisely (Gawiser & Silk 1998). However, as mentioned in the Introduction, it already seems clear that each of the components is needed and that their densities are all comparable. Of course, these arguments provide only indirect evidence for non-baryonic dark matter. More definitive evidence can come only from attempts to detect the hot or cold particles directly. There have been several recent interesting developments in this context, as we now discuss.

Massive Neutrinos. There are now three experiments which indicate a non-zero neutrino mass and hence a non-zero cosmological neutrino density [see Caldwell (1999) for a recent review]. (1) Studies of the ratio of muon and electron neutrinos produced by the decay of pions in the atmosphere suggest that there

are oscillations between muon and tau neutrinos, corresponding to a mass difference $\Delta m^2_{\tau\mu} \approx 2 \times 10^{-3} eV^2$. (2) The deficit of electron-neutrinos coming from the Sun implies that these neutrinos must be oscillating into another neutrino species (labelled "X") with a mass difference, if attributed to the MSW effect, given by $\Delta m^2_{eX} \approx 10^{-5} eV^2$. (3) LSND claims to have detected oscillations between muon and electron neutrinos in neutrino beams coming from accelerator experiments, corresponding to a mass difference $10 eV^2 > \Delta m^2_{\mu e} > 0.2 eV^2$. This is a controversial result but, if true, it implies $m(\nu_\mu) > 0.5 eV$ and hence $\Omega_\nu > 0.005$, which is already comparable to the visible density given by eqn (3). Since the first experiment implies $\Delta m^2_{\tau e} >> 10^{-5} eV^2$, the particle X required to explain the solar neutrino deficit cannot be the tau nuetrino and so would most naturally be identified with the muon neutrino. In this case,

$$m(\nu_\tau) \approx \Delta m_{\tau\mu} \approx 0.05 eV, \quad m(\nu_\mu) \approx \Delta m_{\mu e} \approx 0.005 eV, \quad m(\nu_e) << 0.005 eV. \quad (6)$$

This is consistent with the "see-saw" mechanism and suggests that the total neutrino density is very low. Another possibility, and the only one compatible with the LSND result, is that $m(\nu_\tau) \approx m(\nu_\mu)$, so that one has mass degeneracy and $m(\nu_\tau) >> \Delta m_{\tau\mu}$. In this case Ω_ν could be large and is limited only by the large-scale structure observations (i.e. $\Omega_\nu < 0.2$). However, the solar neutrino problem could not then be atributed to electron neutrinos oscillating into muon neutrinos since $\Delta m_{\mu e}$ would be too large. One would therefore need to identify X with a new "sterile" neutrino, whose mass is very close to that of the electron neutrino, so that $\Delta m_{\mu e} >> \Delta m_{Xe}$. It has been claimed that the sterile neutrino may be useful for astrophysical purposes (eg. in explaining the abundance of r-process elements) but this remains controversial.

WIMPs. Supersymmetry theory requires the existence of a large number extra "sparticles" with a mass in the range $0.1 - 1$ TeV. [See Roszkowski (1999) and Ellis (2000) and for recent reviews.] The Lightest Supersymmetric Particle (LSP) should be stable and observations require that it has neither electric nor strong interactions. Three candidates have been suggested: the (spin 0) sneutrino, the (spin 3/2) gravitino, and the (spin 1/2) neutralino. However, the LEP results imply that the sneutrino mass must exceed 1 TeV, which gives a negligible density, while the gravitino would have a mass of order 1 keV, corresponding to "warm" dark matter. The latter would be inconsistent with large-scale structure observations, although another scenario has recently been proposed in which 100 GeV gravitinos are produced in the context of leptogenesis. The neutralino is therefore the favoured WIMP candidate and this would need to be some mixture of the photino, Higgsino and zino. LEP implies that the mass must be in the

range $30 - 600$ GeV, corresponding to $\Omega_X h^2 \sim 0.1$. One would expect there to be a continual flux of halo neutralinos passing through the Earth and efforts to detect these has been underway for more than a decade. Recently the DAMA group claims to have made a positive detection, associated with the annual modulation of the flux as the Earth goes around the Sun. They find a mass in the range $45 - 76$ GeV but it should be stressed that this depends sensitively on the halo model.

Axions. The axion is a particle associated with the breaking of Peccei-Quinn symmetry at a temperature $f_a \approx 10^{12}$GeV and it aquires a mass m_a due to instanton effects at a temperature $T \approx \Lambda_{QCD}$. In the original thermal production scenario, the associated parameters are

$$\Omega_a \approx \theta^2 (m_a/10^{-6} eV)^{-1.2}, \quad m_a \approx \Lambda_{QCD}^2/f_a \approx 10^{-5} (f_a/10^{12})^{-1} eV \qquad (7)$$

where θ is the "misalignment" angle (Preskill et al. 1983). Several astrophysical constraints require $10^{-6} eV < m_a < 10^{-2} eV$ and microwave cavity searches focus on the mass range $10^{-6} - 10^{-5} eV$. Later it was realized that a network of axion strings could form at the Peccei-Quinn epoch (Davis & Shellard 1989) and axion domain walls could form at the QCD epoch (Shellard 1990). The decay and interaction of these strings and walls could produce an axion density in the range $\Omega_a \approx (100 - 1000)(m_a/10^{-6} eV)^{-1.2}$, which is considerably larger than indicated by eqn (7). Various refinements of these scenarios arise in the inflationary scenarios, depending on whether inflation occurs at a higher or lower temperature than f_a (Shellard & Battye 1998). The combination of the Supersymmetry and Peccei-Quinn symmetry also implies the existence of an axino. In the simplest scenario this has a mass of order a keV and therefore acts like warm dark matter. However, in a more recent scenario the photino decays into an axino and a photon and this predicts a much larger axino density (Covi et al. 1999).

Superheavy Relics. The existence of WIMPs is an inevitable prediction of the "bottom-up" approach of supersymmetry theory. However, one can also adopt various "top-down" approaches (eg. heterotic string theory and minimal supergravity) and these predict the existence of a plethora of particles with much larger mass. For example, Kaluza-Klein theory predicts many helicity states with mass near the Planck mass (Ellis et al. 1990) and the non-thermal decay of inflatons would produce a large density of GUT-mass particles (Kolb 2000). Such particles are sometimes described as "wimpzillas" and their decay might provide a possible explanation of the Ultra-High Energy (UHE) cosmic rays with $E > 10^{19}$GeV. The origin of such cosmic rays is currently unknown but they must originate within 30-50 Mpc (because of the GZK effect) and they do not

seem to be associated with individual galaxies or gamma-ray bursts. Another possible explanation would be the decay of topological defects. In any case, observations of UHE cosmic rays already place interesting constraints on such scenarios (Ziaeepour 1999).

Indirect Detections. There are various ways in which dark matter particles might be detected indirectly. For example, the annihilations of WIMPs in the Galactic halo would produce a flux of positron and antiproton cosmic rays (Bergstrom 1999). Balloon experiments have detected an excess of such particles but it is difficult to identify them specifically with WIMPs. They might also be secondary particles produced by the interaction of primary cosmic rays with interstellar protons and there is much uncertainty associated with the propagation of cosmic rays through the Galaxy and their modulation by the solar wind. WIMP-annihilations would also induce a a Galactic γ-ray background, with a characteristic enhancement of a γ-line near the Galactic centre in the CDM scenario. Such a background may have already been detected with the EGRET satellite (Chary & Wright 1998).

4.   Baryonic Candidates

Over the last few decades, a number of observational claims have been made from time to time which seemed to indicate the existence of MACHOs. Many of these observations turned out to be spurious but they served the useful purpose of stimulating theorists to study cosmological scenarios involving baryonic dark matter and to try to predict their various signatures. Currently one cannot state definitely that MACHOs exist but one can place important constraints on the possible candidates. In this section we will discuss these candidates in turn, focussing particularly on brown dwarfs, red dwarfs, white dwarfs and black holes.

Background Radiation from VMOs. Stars in some range above 8 $M_\odot$ would leave neutron star or black hole remnants but neither of these would be plausible candidates for either the disc or halo dark matter because their precursors would have unacceptable nucleosynthetic yields. Stars larger than 200 $M_\odot$ are termed "Very Massive Objects" or VMOs and might collapse to black holes without these nucleosynthetic consequences (Carr et al. 1984). However, during their main-sequence phase, such VMOs would be expected to generate of a lot of background light. By today this should have been shifted into the infrared or submillimetre band, as a result of either redshift effects or dust reprocessing, so one would expect a sizeable infrared/submillimetre cosmic background (Bond et al. 1991).

Over the last few decades there have been several reported detections of such a background but these have usually turned out to be false alarms. COBE does now seem to have detected a genuine infrared background (Fixsen et al. 1998) but this can probably be attributed to ordinary Population I and II stars. In any case, the current constraints on such a background strongly limit the density of any VMOs unless they form at a very high redshift. For this reason massive Population III stars would need to be pregalactic rather than protogalactic.

Dynamical Effects of SMOs. Stars larger than 10^5 $M_\odot$ - termed "Supermassive Objects" or SMOs - would collapse directly to black holes without any nucleosynthetic or background light production. However, supermassive black holes would still have noticeable dynamical effects and these have been investigated by many authors. The constraints on black holes in our own disc - due to the disruption of open clusters - and in our own halo - due to the heating of disc stars, the disruption of globular clusters and dynamical friction effects - have been discussed in detail by Carr & Sakellariadou (1998). Although it has been claimed that there is positive evidence for some of these effects, such as disc heating (Lacey & Ostriker 1985), the interpretation of this evidence is not clear-cut. It is therefore more natural to regard these dynamical effects as merely imposing an upper limit on the density of black holes or indeed any other type of compact object. It should be stressed that many of these limits would also apply if the black holes were replaced by "dark clusters" of smaller objects, a scenario which has been explored by many authors (Carr & Lacey 1987, Ashman 1990, Kerins & Carr 1994, De Paolis et al. 1995, Moore & Silk 1995).

Halo Light from Red Dwarfs. A particularly interesting recent development was the discovery of red light around NGC 5907 by Sackett et al. (1994), apparently emanating from low mass stars with a density profile like that of the halo. This detection was confirmed in V and I by Lequeux et al. (1996) and in J and K by James & Casali (1996). However, the suggestion that the stars might be of primordial origin (with low metallicity) was contradicted by the results of Rudy et al. (1997), who found that the color was indicative of low mass stars with solar metallicity. Furthermore, it must be stressed that the red light light has only been observed within a few kpc and no NIR emission is detected at 10-30 kpc (Yost et al. 1999). Both these points go against the suggestion that the red light is associated with MACHOs. Recently it has been suggested that the red light seen in NGC 5907 is more likely to derive from a disrupted dwarf galaxy, the stars of which would naturally follow the dark matter profile (Lequeux et al. 1998), or to be a ring left over from a disrupted dwarf spheroidal galaxy (Zheng et al. 1999). In any case, NGC 5907 does not seem to be typical since ISO ob-

servations of four other edge-on bulgeless spiral galaxies give no evidence for red halos (Gilmore & Unavane 1998).

Microlensing of Macrolensed Quasars by LMOs. If a galaxy is suitably positioned to image-double a quasar, then there is also a high probability that an individual halo object will traverse the line of sight of one of the images and this will give intensity fluctuations in one but not both images (Gott 1981). The effect would be observable for objects bigger than $10^{-4}M_\odot$ but the timescale of the fluctuations $\sim 40(M/M_\odot)^{1/2}$y would make them detectable only for $M <$ 0.1 $M_\odot$, so this method works only for "Low Mass Objects" or LMOs. There is already evidence of this effect for the quasar 2237+0305 (Irwin et al. 1989), the observed timescale for the variation in the luminosity of one of the images possibly indicating a mass below 0.1 $M_\odot$ (Webster et al. 1991). However, because the optical depth is high, the mass estimate is very uncertain and a more recent analysis suggests that it could be in the range $0.1 - 10$ $M_\odot$ (Lewis et al. 1998), in which case the lens could be an ordinary star. The absence of this effect in the quasar 0957+561 has also been used to exclude MACHOs with mass in the range $10^{-7} - 10^{-3}M_\odot$ from making up all of the halo of the intervening galaxy, although the precise limit has some dependence on the quasar size (Schmidt & Wambsganss 1998).

Microlensing of Quasars by Jupiters. More dramatic but rather controversial evidence for the microlensing of quasars comes from Hawkins (1993, 1996, 1999), who has been monitoring 300 quasars in the redshift range $1-3$ for nearly 20 years using a wide-field Schmidt camera. He finds quasi-sinusoidal variations with an amplitude of 0.5 magnitudes on a timescale 5 y and attributes this to lenses with mass $\sim 10^{-3}M_\odot$. The crucial point is that the timescale decreases with increasing redshift, which is the opposite to what one would expect for intrinsic variations, although this has been disputed (Alexander 1995, Baganoff & Malkan 1995). The timescale also increases with the luminosity of the quasar and he explains this by noting that the variability timescale should scale with the size of the accretion disc (which should itself correlate with luminosity). A rather worrying feature of Hawkins' claim is that he requires the density of the lenses to be close to critical (in order that the sources are transited continuously), so he has to invoke primordial black holes which form at the quark-hadron phase transition (Crawford & Schramm 1982). However, this requires fine-tuning since the fraction of the Universe going into black holes at this transition must only be about 10^{-9}. Walker (1999) has proposed that Hawkins' lenses might also be jupiter-mass gas clouds.

Microlensing of Stars in the LMC. Attempts to detect microlensing by objects in our own halo by looking for intensity variations in stars in the Magellanic Clouds and the Galactic Bulge have now been underway for a decade (Paczynski 1996). This method is sensitive to lens masses in the range $10^{-7} - 10^2 M_\odot$ but the probability of an individual star being lensed is only $\tau \sim 10^{-6}$, so one has to look at many stars for a long time (Paczynski 1986). The duration and likely event rate are

$$P \sim 0.2(M/M_\odot)^{1/2}y, \quad \Gamma \sim N\tau P^{-1} \sim (M/M_\odot)^{-1/2}y^{-1} \tag{8}$$

where $N \sim 10^6$ is the number of stars. The MACHO group currently has 13-17 LMC events and the durations span the range $34 - 230$ days (Alcock et al. 2000). For a standard halo model, the data suggest an average lens mass of around 0.5 $M_\odot$ and a halo fraction of 0.2, with the 95% confidence ranges being $0.15 - 0.9$ $M_\odot$ and $0.08 - 0.5$. The mass is comparable with the earlier estimates but the fraction is somewhat smaller (Alcock et al. 1997). This might appear to indicate that the MACHOs are white dwarfs but one could also invoke a less conventional candidate. For example, primordial black holes forming at the quark-hadron phase transition might have the required mass (Jedamzik 1997) and the microlensing implications of this scenario are discussed by Green (2000). Perhaps the most important result of the LMC searches is that they *eliminate* many candidates. Indeed the combination of the MACHO and EROS results already excludes objects in the mass range $5 \times 10^{-7} - 0.002$ $M_\odot$ from having more than 0.2 of the halo density (Alfonso et al. 1997).

White Dwarfs. A few years ago white dwarfs (WDs) were regarded as rather implausible dark matter candidates. One required a very contrived IMF, lying between 2 $M_\odot$ and 8 $M_\odot$, in order to avoid excessive production of light or metals (Ryu et al. 1990); the fraction of WD precursors in binaries would be expected to produce too many type 1A supernovae (Smecker & Wyse 1991); and the halo fraction was constrained to be less than 10% in order to avoid the luminous precursors contradicting the upper limits from galaxy counts (Charlot & Silk 1995). The observed WD luminosity function also placed a severe lower limit on the age of any WDs in our own halo (Tamanaha et al. 1990). More recent constraints - from CNO production (Gibson & Mould 1997), helium and deuterium production (Field et al. 2000) and extragalactic background light limits (Madau & Pozzetti 1999) - have strengthened these limits (Graff et al. 1999). At least some of these limits must be reconsidered in view of recent claims by Hansen (1998) that metal-poor old WDs with hydrogen envelopes could be much bluer and brighter than previously supposed, essentially because the light emerges from deeper in the atmosphere. This suggestion has been supported by HST

observations of Ibata et al. (1999), who claim to have detected five candidates of this kind. The objects are blue and isolated and show high proper motion. They infer that they are 0.5 $M_\odot$ hydrogen-atmosphere WDs with an age of around 12 Gyr. Three such objects have now been identified spectroscopically (Hodgkin et al. 2000, Ibata et al. 2000), so this possibility must be taken very seriously. However, this does not circumvent the nucleosynthetic arguments against WDs.

Brown Dwarfs. Objects in the range $0.001 - 0.08$ $M_\odot$ would never burn hydrogen and are termed "brown dwarfs" (BDs). They represent a balance between gravity and degeneracy pressure. It has been argued that objects below the hydrogen-burning limit may form efficiently in pregalactic or protogalactic cooling flows (Ashman & Carr 1990, Thomas & Fabian 1990) but the direct evidence for such objects remains weak. While some BDs have been found as companions to ordinary stars, these can only have a tiny cosmological density and it is much harder to find isolated field BDs. The best argument therefore comes from extrapolating the initial mass function (IMF) of hydrogen-burning stars to lower masses than can be observed directly. The IMF for Population I stars ($dN/dm \sim m^{-\alpha}$ with $\alpha < 1.8$) suggests that only 1% of the disc could be in BDs (Kroupa et al. 1995). However, one might wonder whether α could be larger, increasing the BD fraction, for zero-metallicity stars. Although there are theoretical reasons for entertaining this possibility, earlier observational claims that low metallicity objects have a steeper IMF than usual are now discredited. Indeed observations of Galactic and LMC globular clusters (Elson et al. 1999) and dwarf spheroidal field stars (Feltzing et al. 1999) suggest that the IMF is *universal* with $\alpha < 1.5$ at low masses (Gilmore 1999). This implies that the BD fraction is much less than 1% by mass. However, it should be stressed that nobody has yet measured the IMF in the sites which are most likely to be associated with Population III stars. We have seen that the LMC microlensing results would now seem to exclude a large fraction of BDs in our own halo. Although Honma & Kan-ya (1998) have presented 100% BD models, these would require falling rotation curves and most theorists would regard these as rather implausible.

5.   Conclusions

1) Cosmological nucleosynthesis calculations suggest that there is both baryonic and non-baryonic dark matter. From a theoretical perspective, the latter is better motivated since one cannot be sure that the dark baryons are inside galaxies. The more conservative conclusion would be that they are contained in an intergalactic medium or in gas within groups or clusters of galaxies.

2) Over the years there have been several observational claims which seem

to indicate the existence of MACHOs but these have usually turned out to be false alarms. Currently the only *positive* evidence comes from microlensing observations and the LMC results suggest that white dwarfs may be the best MACHO candidate. However, it must be stressed that the mass estimate upon which this inference is based is sensitive to assumptions about the halo model and the large number of arguments which have been voiced against white dwarfs in the past cannot be brushed aside too cavalierly.

3) There are still many viable non-baryonic candidates. As with the baryonic candidates, there have been a number of flase alarms in the past. However, the most recent experimental results require that there be at least some hot dark matter in the form of neutrinos and there are also clams to have detected cold dark matter in the form of WIMPs.

4) We have seen that there are many important *constraints* on both baryonic and non-baryonic dark matter candidates from a wide variety of other astrophysical effects. Until there is a definite detection, therefore, the best strategy is to proceed by *eliminating* candidates, on the Sherlock Holmes principle that whatever candidate remains, however implausible, must be correct.

1. Alcock, C. et al. 1997, ApJ 486, 697
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